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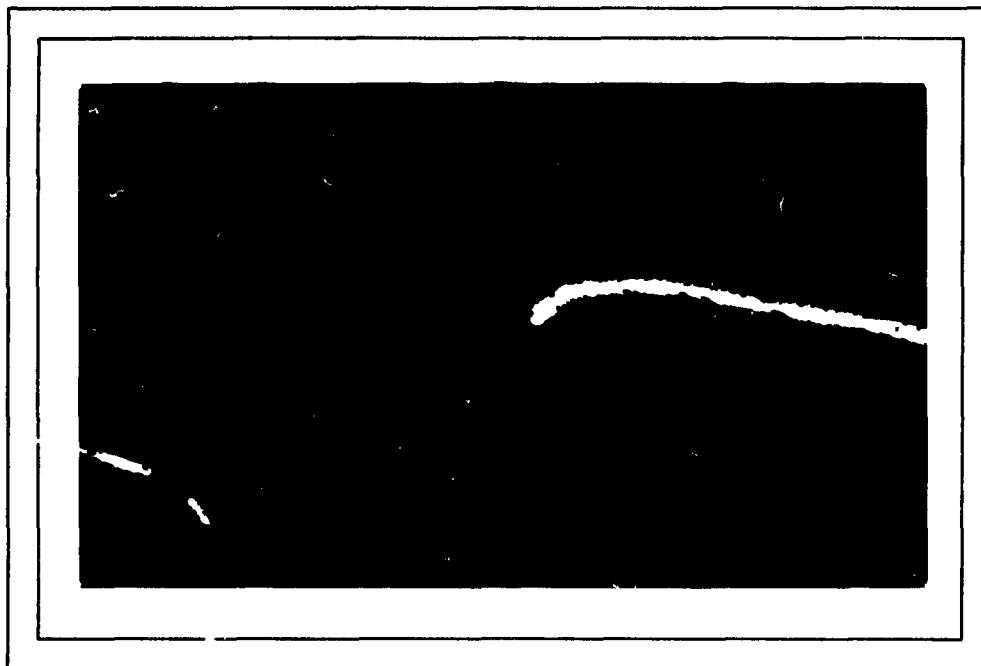
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OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

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**"Atmospheric Excitations Produced by
Fast Electrons"**

by
Richard E. Payne

Project 8605

Task 86050

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Abstract

Title of thesis: **Atmospheric Excitations Produced by Fast Electrons**

Richard Earl Payne, Master of Science, 1962

Thesis directed by: **Professor S. Fred Singer**

Fast electrons with energies in the kev and mev range produce a spectrum of secondary, tertiary, etc. electrons in the upper atmosphere by ionizing air molecules. The secondary and lower order electrons have energies less than 150 ev but the total number produced is large compared to the number of primaries so that a considerable proportion of the total energy is possessed by the secondaries. The secondaries can therefore be significant in exciting molecules and producing light.

The experiments described in this paper show that electrons with energies of less than 150 ev colliding with air molecules at pressures of 10^{-8} to 10^{-2} mm. of Hg produce a spectrum in the 3000 A to 5000 A range which is similar to that in the aurora. The principal spectral lines are from the second positive and first negative systems of molecular nitrogen. The intensities of the two systems agree with theoretical calculations which show that they should be of the same order of magnitude and more intense than other systems in this wavelength range.

The efficiency of the process, defined as the ratio of the rate at which energy leaves the system in the form of radiation to the rate at which energy enters in the electron beam, is calculated to be of the order 5×10^{-4} for the system used in the experiments.

An experiment is described in which an electron gun will be carried into the upper atmosphere by a rocket to give another test of the efficiency of the light producing process.

Preface

Physicists studying the phenomena of the aurora have developed theories of its origin which have mostly dealt with high speed charged particles which ionize and excite air molecules in the upper atmosphere.

The purpose of the research represented in this thesis was to examine the spectra produced in the laboratory by electrons with energies of less than 150 ev. The results are compared to experimental data on the aurora and results of calculations on electron beams in air.

ACKNOWLEDGMENTS

I wish to express my appreciation for the guidance of my advisor, Professor S. F. Singer during the writing of this thesis and the research leading to it. I should also like to thank J. Bohse and R. Bettinger for help and advice in building the instrument package for the rocket and D. Sekira of Westinghouse Electric Corp. who very kindly exerted a great deal of effort to provide the electron guns for the rock.

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CHAPTER I

COLLISIONS OF ELECTRONS WITH AIR MOLECULES

Theories of the origins of the aurora deal mainly with the interactions of high energy electrons and air molecules and atoms. These interactions consist of collisions which ionize and excite the atoms and molecules.

Experimentally, and theoretically in the case of hydrogen, high energy primary electrons in a gas collide with the atoms and molecules and produce a spectrum of low energy secondaries. The distribution of electrons is not known for gases other than atomic hydrogen. Since the secondary electron distribution is insensitive to detailed atomic structure, the distribution in air should be fairly close to that in atomic hydrogen. Table 1¹ shows the energy distribution of secondary electrons for high-velocity impacts in atomic hydrogen. These calculated values fall between two sets of measurements in

Table 1

Secondary Electron Spectrum from Ionization by High-Velocity Impacts of Electrons in a Gas of Hydrogen Atoms (Meyerott, Physics of the Ionization Processes in Air, Table A-11, p. A-5)

Energy of Secondary Electrons, ev	Energy of Incident Electrons, ev			
	10^3	10^4	10^5	10^6
	(Percentage of all secondary electrons)			
0 - 3.39	33.0	35.4	37.3	38.9
3.39 - 6.77	17.9	18.5	19.0	19.5
6.77 - 13.54	17.9	17.7	17.7	17.7
13.54 - 27.1	13.7	12.7	12.2	11.7
27.1 - 40.6	5.3	4.7	4.3	4.0
40.6 - 67.7	5.5	4.6	4.0	3.5
67.7 - 135.4	4.1	2.5	3.1	2.5
over 135.4	2.5	3.1	2.6	2.2

air, one at 7 to 14 kev², and the other at 100 to 500 ev³. The individual sets of measurements showed little variation with energy of the primary electron but had considerable difference between them.

In the case of a gas of atomic hydrogen, calculations⁴ show that the number of primary ion pairs produced by a high velocity electron is $E_p/60$ where E_p is the energy of the primary. Calculations and experiments⁵ show that the total number of ion pairs produced by high velocity electrons is $E_p/37$ where this number includes the ionizations by the secondary and lower order electrons. Valentine and Curran⁶ show that a primary proton or electron loses on the average about 35 ev for every ion pair produced in air.

We are particularly interested in electrons in the low energy region, less than 150 ev. By the time they have reached this region the primary electrons have lost 90 per cent or more of their original energy and are not as interesting as the secondary and lower order electrons. The number of these electrons is about $\frac{E_p}{35}$ so that the number of lower order electrons is larger than the number of primaries for $E_p > 35$ ev. A look at Table 1 shows that there is a considerable amount of energy distributed among the secondaries and that about 30 per cent of them have enough energy to ionize further. Therefore these lower order electrons are quite important in producing the spectra that arise from high energy electrons passing through air.

Experimental studies by Tate and Smith⁷ and earlier by Smith⁸, combined with theoretical estimates by Schiff and Marton⁹, show that the probability of ionization for the gases in which we are interested rises from zero at the ionization potential to a maximum near 150 ev after which it steadily decreases. For any particular energy, the absolute probabilities of ionization are about the same for the principal gases in air.⁷

The experiments described on the following pages were undertaken to determine the spectra produced by electrons with energies of less than 150 ev when colliding with air molecules. From these spectra are calculated absolute intensities of the spectral lines and an estimate of the efficiency of the electrons in producing photons.

CHAPTER II

EXPERIMENTAL METHOD

A beam of electrons of energies varying from 50 ev to 150 ev was used to excite and ionize gas molecules and ions in a vacuum bell jar at pressures of 5×10^{-4} to 10^{-2} mm of mercury. The light resulting from the de-excitation and recombination was focused on the entrance slit of a Jarrell-Ash two-meter spectrometer by a system of two lenses. Photographs were taken of the spectrum in the wavelength range 3500 to 6000 Å and the wavelengths of the spectral lines determined.

A. Electron Gun

A primary consideration was the electron gun. It was desired that it be simple, easy to build and replace, and capable of producing a beam which would make enough light to be photographed with the spectrometer. The last requirement meant also that the beam should be fairly small in cross section.

1. Filaments: Since it was necessary to be able to open the vacuum system from time to time and the parts were to be easily replaceable, it was decided that tungsten filaments would be the most suitable. A convenient source of tungsten filaments of a satisfactory size was found to be 40 watt fluorescent light tubes. When heated with 100 to 200 watts they yielded a current on the order of one ampere. At the temperature at which this current was available the filaments had lifetimes of several hours. The operating power was determined by increasing the current through the filament until it failed. A value of about 10 per cent less than the failure current was used in the experiments.

When anode voltages of greater than 100 volts were used it was found necessary to replace the filaments for an hour or so at working temperature and at a pressure well below that to be used in the experiment. Otherwise arcing

and discharges occurred when the anode voltage was turned on which sometimes burned out the filament. The best method for reaching the conditions used in the experiments was found to be the following:

1. Outgas the filament for approximately one hour with 0.95 amps/filament flowing through the filament at a pressure of about 10^{-5} mm of Hg.
2. Turn off the filament.
3. Set the anode voltage at the value to be used in the experiment.
4. Slowly increase the filament current from zero to 0.95 amps/filament, the value used in the experiments. Do not let the pressure rise above about 10^{-6} mm of Hg in this step.
5. Increase the pressure to the value to be used in the experiment.

Since sufficient power was available, two filaments were connected in parallel in all of the experiments.

Another reason for using the fluorescent tube filaments beyond the fact that they gave sufficient current was that they were a convenient size dimensionally. The anode chosen was an aluminum disc with a hole in the center with a diameter the same as that desired for the beam. Any electrons coming from a part of the filament not beneath the hole would go directly to the anode and not contribute to the beam current.

2. Anode: Several types of anodes were tried to see if any would contribute to the beam current a significantly larger proportion of the electrons leaving the filament than the others. One did, but the beam in its case was of large diameter and fairly diffuse so that it was decided not to use it.

Four different anodes were tested:

- i. A disc 4" in diameter and with a $7/8$ " hole in the center gave the most well defined beam and was the anode used in the experiments. The hole size was chosen for two reasons.

One, it was desired to have a beam about 1" in diameter. Anything larger than this would not have contributed to the light going to the spectrograph. Two, according to Maloff and Epstein¹⁰, beam current increases with the solid angle that the anode hole subtends at the cathode. This, of course, is also another reason for the choice of filaments. They gave a good beam size.

- ii. A disc of copper window screen wire was mounted on an aluminum ring with inside diameter $3 \frac{1}{4}$ " and outside diameter 4". This gave the highest proportion of beam current but not by a factor large enough to counteract the fact that the beam was larger in diameter and therefore a more diffuse light source.
- iii. A wire ring, $7/8$ " in diameter, of No. 10 wire was supported by three thin wires connected to the ring used to support the screen wire in b. This gave approximately the same proportion of beam current as a.
- iv. This was another wire ring, the same as c except that the wire size was No. 18.

Experimental setup:

The filament was supported by its connecting wires. The anode stood on top of three plexiglass legs. The walls and top of the bell jar were lined with screen wire. This was connected to the same potential as the anode and the current to the screen was assumed proportional to the beam current.

Typical values:

Total current was quite sensitive to pressure changes. Since the pressure varied slightly among the readings, absolute values of the current

were not important. What was sought was the ratio of the current to the screen wire to the total current.

Anode	I_{anode}	I_{screen}	I_{total}	Ratio
a.	9.7 ma	7.3 ma	17.0 ma	.57
b.	17	4.7	21.7	.78
c.	10	7.5	17.5	.57
d.	18	7.5	29	.62

3. Filament-Anode spacing: According to Maloff and Epstein¹⁰, the beam current increases with decreasing cathode-anode spacing, reaching a maximum at zero spacing. The support pieces of the filaments extended under the anode so the filaments were brought as close as possible to the anode with no risk of contact. This distance was about 1/8". Another effect which dictated some spacing was beam spreading. The beam was conical shaped and became wider as the filament-anode distance was decreased. One-eighth inch spacing gave a reasonable beam shape. The values chosen gave a cone with an angle of about 30 degrees.

4. Beam current. During the recording of the spectra it was decided that a measure of the efficiency of the photon-producing process would be a useful result. Since the quantity measured in the experiment was the total current reaching the anode it was necessary to make an accurate determination of what proportion of the anode current was contributed by the beam.

A metal cylinder with one open end and diameter the same as that of the anode was inverted over the anode. The space between them was 1/2". The anode and the beam collector were maintained at equal positive potentials. It was found that the fraction of the total current in the beam decreased with increase in the total current from a value of .2 at 2.5 ma to .06 at 100 ma. Beyond 100 ma it remained constant.

B. Pressure

The light output from the electron beam was, of course, quite sensitive to the density, i.e. pressure, of the air in the vacuum system. The reason for this is the decrease in mean free path of electrons with an increase in pressure. At pressures below 10^{-4} many of the electrons will not undergo collisions before they reach the walls of the vacuum system. As the pressure increases, the probability of collisions within the vacuum system increases. Also the mean free path of the electron decreases so that the area of collisions, i.e. source of light, decreases and the light source becomes more intense. More of the light produced can then be focused on the spectrometer slit.

There was an upper limitation also to the pressure range which could be used. Discharge began at pressures of 10^{-3} to 10^{-2} mm of Hg depending on the anode voltage. The pressure range used was determined by finding the pressure at which discharge began for the voltage used. Pressure was then kept slightly below this value in as small a range as was practical with the available method of regulating the pressure.

Pressure regulation was difficult because the only leak valve in the vacuum system was between the oil diffusion pump and the mechanical pump. The method used to maintain pressures was then necessarily not the best that might have been devised had there been a leak directly into the bell jar. First, the power to the oil diffusion pump was reduced so that only about 75 volts appeared across the heating coils instead of 110. Then, air was leaked in slowly through the leak valve until a position of the valve was found which would maintain the pressure desired. Several adjustments of the valve were usually found necessary during an exposure. Leaking air in through the leak valve increased the back pressure on the oil diffusion pump and decreased the pumping speed.

C. Optics

An optical system consisting of two lenses was used to focus the image of the electron beam on the spectrometer slit. The lenses were 3" in diameter and had a 4.5" focal length. One was inside the vacuum chamber and the other outside, as shown in Fig. 1.

A stop was included between the lenses and outside the bell jar to prevent light other than that from the electron beam from reaching the slit.

D. Anode power sources

For early experiments a D.C. power supply was used which supplied about 300 volts. However, at the currents which the system drew, this loaded badly and one exposure using this supply was taken at 50 volts because of the high current drawn. Later, a storage battery supply, used normally for powering the carbon arc, was substituted. This gave 160 volts at as much current as was needed. As mentioned before, the excitation and ionization of molecules and atoms has a maximum efficiency at electron energies of about 150 ev. For this reason the battery supply was preferable.

E. Tungsten evaporation

Since the filaments were operated at temperatures approaching the point at which they failed, a considerable amount of tungsten was "boiled" off and deposited on all surfaces inside the bell jar. A heavy coating of tungsten on the lens and the part of the bell jar through which light passed would have cut down the intensity of the light reaching the spectrometer slit. Since the filaments were replaced for each exposure, the lens and bell jar (in the area where light passed through) were cleaned while the system was open.

F. Photography

The light from the electron beam was quite dim. The lines were not visible with the naked eye in the spectrometer. Photographing the spectra thus became a problem. Kodak Double-x and Tri-x panchromatic films were

tried. For the length of exposures necessary, Double-x was preferable to Tri-x both in grain size and apparent speed. The term "apparent speed" is used for several reasons.

1. The length of exposure varied from one to six hours. The film speed supplied by the manufacture, does not strictly apply in cases where the exposures are so long.
2. Quantities such as pressure and anode voltage varied somewhat over the length of an exposure so that it was not possible to take two pictures exactly alike.

Nevertheless, Double-x definitely did seem to allow a better exposure in less time. There was no doubt in the improved grain size with Double-x film.

In making a choice of this type, allowances must be made for the equipment which will be used to evaluate the results. In this case the comparator used to find the wavelengths of the spectral lines had a bearing on the choice of film.

The comparator used employed a microscope with a fairly high magnification. The higher the magnification, the smaller the area of film which appears in the eyepiece. For a very narrow spectral line such as those that appeared in the mercury reference spectra this does not make much difference for the order of magnitude of magnification and diameter of objective lens in the comparator. However, when viewing molecular spectra, one sees not only discrete lines but bands. The weaker bands that appear on the film will often seem like very wide lines that change density gradually. For many of them the spectrometer cannot resolve the lines in the band. In a case like this the band may spread over a considerable portion of the field of view of a medium powered microscope; then the change in density will be very difficult to see. In a case like this, the line may be seen more easily with the naked eye or under very low magnification (2x, 3x). For several of the

lines in the spectra it was necessary to find the approximate position of the line using a millimeter rule and a low power (3x) magnifier. Knowing the approximate position one could then usually find the line with the comparator microscope.

Development

Two types of developers were used. Kodak Microdol developer was available and was used in early experiments. As soon as it could be procured, Kodak Microdol-x was used for better contrast and finer grain.

Since exposures were difficult it was desired to get as much as possible out of each exposure. Following this line of reasoning, the exposures were overdeveloped for maximum contrast. The development procedures for the two types of developers were as follows:

Microdol

Development; twenty minutes with agitation at 30-second intervals

Rinse; thirty seconds

Fix; Kodak Rapid Fixer for four minutes

Rinse; three minutes

Microdol-x

Development; sixteen minutes with agitation at 30-second intervals

Rinse; thirty seconds

Fix; Kodak Rapid Fixer for four minutes

Rinse; three minutes

The development times were determined by experiment as giving maximum contrast.

Chapter III

Wavelength Measurements

A. Spectral Analysis

The lines and band heads found are listed in Table III with the mercury lines used for a comparison spectrum. The principal source for identifications was Pearce and Gaydon¹². Two sets of lines appear, one of which is from an exposure of three hours at an anode voltage of 50 volts. The second set is from an exposure of six hours at an anode voltage of 100 volts.

It is obvious from Table III that the lines come principally from the nitrogen molecule, more specifically from the first negative and second positive systems. Conspicuous is the absence of any lines due to oxygen. Table II gives a distribution of ions produced by 50 ev electrons moving through air. From this distribution we can see that indeed the molecular nitrogen should provide most of the spectra

Table II

Distribution of Positive Ions Produced by 50 ev Electrons in Air (Meyerott, Physics of the Ionization Processes in Air, Table A-11, p. A-12)

Ion	Per cent
N_2^+	62.5
N^+	22.5
O_2^+	12.5
O^+	2.5

The use of panchromatic film set a lower limit of about 3000 Å to the range of wavelengths which could be photographed. The upper limit of 6000 Å was set by the spectrometer. All lines were found in the interval 3500 Å to 5000 Å.

B. Wavelength uncertainties

The principal uncertainties arise from the finite line width. In order to get reasonable exposure times, a slit opening of 50μ was used. Molecular spectral lines tend to be diffuse rather than sharp like atomic lines.

These two effects gave an uncertainty of about 0.5 Å.

Table III

Wavelength, Intensities, and Identification of Spectral Lines Produced by 50 ev and 100 ev Electrons in Air[†]

<u>Wavelengths (Å)</u>		<u>Relative intensities</u>		<u>Absolute Intensities</u>		<u>Identification</u>
<u>50 ev **</u>	<u>100 ev</u>	<u>50 ev</u>	<u>100 ev</u>	<u>50 ev</u>	<u>100 ev</u>	
	Hg ref. Spectr.					
	3125.66					
	3131.55					
	3131.83					
	3341.48					
3371.1		1.0		1.1		3371.3 $M(2^+)$
3536.2	3536.8	1.3		1.3		3536.7 $M_2^+(2^+)$
	3564.6		1.1		.50	3564 $M_2^+(1-)$
	3573.2					
3576.1	3577.3	4.3	2.2	4.7	1.0	3576.9 $V M_2(2^+)$
3581.9	3582.9	1.7	2.9	1.9	1.3	3582.1 $V M_2^+(1^-)$
	3650.15					
	3654.83					
	3662.88					
	3663.28					
3754.5	*3725					3755 $M_2(2^+)$
	*3781	1.1				
	3796.9					
	3798.6					
	3799.7					
	3800.9					
	3801.9					
	3803.0					
3804.5	3804.1	1.8	1.0	2.0	0.5	3804.9 $V M_2(2^+)$
	3805.2					
	3806.7					

[†] For notation see end of table.

Table III (Cont'd)

<u>Wavelengths (Å)</u>		<u>Hg ref. Spectr.</u>		<u>Relative Intensities</u>		<u>Absolute Intensities</u>		<u>erg min</u>		<u>Identification</u>
<u>50 ev</u>	<u>100 ev</u>	<u>50 ev</u>	<u>100 ev</u>	<u>50 ev</u>	<u>100 ev</u>	<u>50 ev</u>	<u>100 ev</u>	<u>50 ev</u>	<u>100 ev</u>	
3808.5										3854.7 + M_2 V-K Bands 3858 M_2 (1-) 3861.9 V CN 3871.4 V CN
3810.1										
3812.2										
3814.1										
3816.3										3884.3 V M_2^+ (1-) 3888.65 He
3818.7										
3855.3										
3858.7										
3861.4				1.0	1.0	1.1	0.5			3884.3 V M_2^+ (1-) 3888.65 He
3871.1				1.4	1.5	1.5	0.7			
3874.0										
3875.9										
3877.9										3884.3 V M_2^+ (1-) 3888.65 He
3879.9										
3881.6										
3884.0										
3884.1				3.1	4.6	3.4	2.1			3884.3 V M_2^+ (1-) 3888.65 He
3886.6				2.1	4.6	2.3	2.1			
3887.5				1.8	2.0					
3888.1										
3889.0				1.8		2.0				3884.3 V M_2^+ (1-) 3888.65 He
3889.7				2.5	1.6	2.8	0.7			
3891.1				1.7	1.4	1.9	0.6			
3892.6				3.3	2.5	3.6	1.1			
3894.1				3.4	1.5	3.7	0.7			3884.3 V M_2^+ (1-) 3888.65 He
3895.3				4.2	3.9	4.6	1.8			
3896.1				4.1	2.2	4.5	1.0			
3897.9				4.6	5.4	5.1	2.4			
3899.1				1.8	3.0	2.0	1.4			3884.3 V M_2^+ (1-) 3888.65 He
3900.2				4.8	7.0	5.3	3.2			
3901.4				3.3	4.1	3.6	1.8			
3902.5				4.9	8.2	5.4	3.7			
3903.5				4.0	4.7	4.4	2.1			
3904.6										

Table III (Cont'd)

Wavelengths (Å)		Relative Intensities		Absolute intensities $\frac{\text{erg}}{\text{min}}$		Identification
50 ev	100 ev	50 ev	100 ev	50 ev	100 ev	
	</					

Table III (Cont'd)

<u>Wave lengths (Å)</u>		<u>Relative Intensities</u>		<u>Absolute Intensities $\frac{\text{erg}}{\text{min}}$</u>		<u>Identification</u>
<u>50 ev</u>	<u>100 ev</u>	<u>50 ev</u>	<u>100 ev</u>	<u>50 ev</u>	<u>100 ev</u>	
Hg ref. Spectr.						
4044.5						
4046.56						
4077.81						
4236.7	4102.5		1.2		0.5	4102.3 V C ₂
	4199.5					4199.1 V N ₂ ⁺ (1 ⁻)
4252.9	4237.2	1.0	3.0	1.1	1.4	4237 N ₂ ⁺ (1 ⁻)
4256.3	4249.6		1.3		0.6	4248.9 R CO ⁺
4259.5	4253.3		2.2		1.0	
4262.4	4255.1		1.6		0.7	
4265.0	4256.7		2.3		1.0	
4267.4	4258.9		1.4		0.6	
4271.8	4260.0	1.1	2.5	1.2	1.1	
4278.2	4261.6		1.5			
	4262.9	1.2	2.7	1.3	0.7	
	4264.1		1.8		0.8	
	4265.6	1.4	3.2	1.5	1.4	
	4266.8		1.6		0.7	
	4268.0	1.5	3.6	1.7	1.6	
	4269.1		1.7		0.8	
	4270.2	1.2	2.9	1.3	1.3	
	4271.2					
	4272.5	1.0	3.0	1.1	1.4	
	4278.8	9.4	15.2	10.4	6.8	4278.1 V N ₂ ⁺ (1 ⁻)
	4283.4		1.1		0.5	
	4286.8		0.9		0.4	
	4289.6		0.8		0.4	
*4339.2	4341.2		2.2		1.0	4340.47 H

Table III (Cont'd)

<u>wavelength (A)</u>	<u>Relative Intensities</u>				<u>Absolute intensities</u>		<u>erg min</u>	<u>Identification</u>
<u>50 ev</u>	<u>100 ev</u>	<u>Hg ref. Spectr.</u>	<u>50 ev</u>	<u>100 ev</u>	<u>50 ev</u>	<u>100 ev</u>		
			4317.50					
			4358.35					
			</					

Symbols:

Letters following wavelengths:

V - Band shaded to violet

R - Band shaded to red

* Line found on densitometer trace, uncertainty is $\pm 10\text{\AA}$

Lines listed consecutively with no spaces mean that they appear to belong to the same band.

** Some lines which appear in the 100 ev spectrum do not appear in the 50 ev spectrum because the source was not as bright at the lower energy.

CHAPTER IV

INTENSITY MEASUREMENTS

A. Relative Intensities

It was first attempted to obtain the intensities of the spectral lines directly by using a 1P21 photomultiplier tube in conjunction with the spectrometer. This spectrometer has a set of slits which fit over the exit slit and a wavelength drive mechanism to sweep the spectrum at a constant rate. Unfortunately, however, the light level proved to be too low for the use of a photomultiplier. According to Zworykin²⁴, any light which can be photographed with an exposure of less than two hours can be detected by a photomultiplier. However, as the light level decreases, the use of more subtle techniques such as cooling the phototube and pulsing the incident light are required to improve the signal to noise ratio. The light from the electron beam was near the stated lower limit. Cooling the tube below the temperature of dry ice was impossible with available apparatus because the photomultiplier had to be mounted inside the spectrometer at the exit slit. Therefore it was determined that the intensities of the spectra could not be obtained with a photomultiplier tube.

The means chosen for obtaining the intensities was that of calibrating the film in terms of density of film vs. relative intensity and using a carbon arc for a source of a known intensity.

A seven step filter was used to calibrate the film. The step filter was inserted in a photographic enlarger and its image focused on Double-x film below. The enlarger made it possible to obtain an enlarged exposure of the step filter which was easier to analyze.

In order to minimize uncertainties due to varying sensitivity of the film at different wavelengths, the light from the step filter was passed through an interference filter before reaching the film. The interference

filter passed light of 4554 Å with a bandwidth of about 50 Å.

A number of different exposures of the step filter were taken and those were kept whose range of densities most closely matched that of the spectra.

From the step filter exposures a density-relative intensity was drawn. Density was measured with a Jarrell-Ash densitometer which recorded the results on a Brown recorder. Since the sensitivity of the densitometer varied from one use to another, a trace of the appropriate step filter was taken immediately preceding and following the recording of a spectrum density to provide a scale for relative intensity determinations.

Since the film did not have enough latitude to cover the range of intensities of the spectral lines observed, two exposures were taken at each of the two electron energies.

B. Carbon arc

The determination of absolute intensities required a standard for which a carbon arc was used. The intensity of the light from the anode can be calculated by considering it as a radiator with a known emissivity. The results agree with standard tungsten lamps within two percent. Fortunately, the intensity of the light from the anode is not a sensitive function of the current in the arc.

The carbon arc is an extremely intense light source. Since there is no provision on the Jarrell Ash spectrometer for exposure times of less than something of the order of a second, it was necessary to decrease the intensity by means of a grey filter between the arc and the entrance slit of the spectrometer.

A lens was used to focus the image of the anode of the carbon arc on the spectrometer entrance slit.

A convenient way of making a simple grey filter is to place a number of sheets of screen wire in the path of the light. The filter used in this experiment consisted of seven sheets of ordinary copper screen wire. The attenuation factor of this filter was 15.7

For more precision than was available with film over the attenuation range of the filter, the attenuation factor was determined using a photomultiplier tube. The light incident on the tube was such that the output current was well within the linear range of the tube. The procedure used was to measure the output current with and without the filter in the path of the light. The attenuation factor was then the ratio of the two current readings. In order to determine whether the filter really was a grey filter, an attenuation factor was determined for both white light and light of wavelength 4554 Å. The factors agreed within 15 percent. The filter was decided to have an attenuation factor which would have much less uncertainty over the wavelength range in which the spectra appeared than the uncertainties inherent in measuring light intensities by density of photographic film.

An approximation was made in considering the response of the film to light to be linear with time. In other words, it was assumed that the density of the film was a function of the integrated light incident and not of the rate at which it is incident. This is not strictly true; however, any measurement of the dependence on rate would have involved the same uncertainties inherent in the measurement of the intensities of the spectral lines. These uncertainties arose primarily from converting film density to intensity of light.

C. Analysis of Intensities

The Planck formula for gray body radiation is

$$B(\lambda, T) = \frac{c^2 h}{\lambda^5} \frac{2a \, d\lambda}{e^{ch/kT\lambda} - 1}$$

where

$$c^2 h = 5.96 \times 10^{-6} \frac{\text{erg cm}^2}{\text{sec.}}$$

$$\frac{hc}{k} = 1.44 \text{ cm deg}$$

for the carbon arc $T = 3995^\circ \text{K}$

$$a = a(\lambda)$$

a varies from 0.708 for $\lambda = 2600 \text{ A}$

to 0.767 for $\lambda = 7800 \text{ A}$

Since the carbon arc intensity curve is so steep in the wavelength region we are interested in only a small part of it which was in a range where the density of the film could be measured with reasonable accuracy. A convenient wavelength in this range at which to compute the intensity is 3450 A.

$d\lambda$ was computed from the apparent width on the film of lines in the mercury spectrum which were known to be very narrow. An average of six of these gave a value of $.74 \pm .02 \text{ A}$

Computing the value of the exponential

$$e^{\frac{ch}{kT\lambda}} = e^{\frac{1.44 \times 10^5}{3.45 \times 3995}} = e^{10.47}$$

we see that we can substitute $e^{\frac{ch}{kT\lambda}}$ for $e^{\frac{ch}{kT\lambda} - 1}$.

Computing B for $\lambda = 3.45 \times 10^{-5} \text{ cm}$ and $T = 3995^\circ \text{K}$

$$B(\lambda, T) = 4.04 \times 10^4 \text{ erg/sec/cm}^2$$

The area of the carbon anode is $.384 \text{ cm}^2$. Thus the total energy radiating from the anode is $4.04 \times 10^4 \times .384 = 1.55 \times 10^4 \text{ erg/sec}$.

The length of exposure of the carbon arc was one second, therefore the total amount of energy reaching the film was $.99 \times 10^8$ erg. This corresponds to a value of 5.0 on the relative intensity scale derived from the step filter. Thus, for the exposure from the 50 ev electrons which lasted three hours the rate at which energy reached the film which corresponded to 5.0 relative intensity is $\frac{.99 \times 10^8}{3 \times 60} = 5.50$ erg/min. For the exposure for the 100 ev electrons which lasted six hours the rate is $\frac{.99 \times 10^8}{6 \times 60} = 2.25$ erg/min. On this basis the scale of absolute intensities is set up.

Meyerott¹⁵ computes the fluorescence efficiency for the band heads in the N_2^+ first negative, N_2 second positive, and N_2 first positive band system. He defines fluorescence efficiency as the quantity

$$\frac{\sigma_{ix}}{\sigma_{ia}} \frac{h\nu}{34\text{ev}}$$

where σ_{ix} is the ionization cross section for the band head, σ_{ia} is the ionization cross section for air, $h\nu$ is the energy of the emitted spectral photon (inev). His value of the fluorescence efficiency for the N_2 second positive system is about 1/3 less than that for the N_2^+ first negative. There are no absolute cross sections available for the N_2 first positive band system but Meyerott estimates that the fluorescence efficiency for this system is of the same order of magnitude as that of the N_2 second positive. Table III shows that since the N_2^+ first negative and N_2 second positive band systems are the only nitrogen band systems which appear, they must indeed have fluorescence efficiencies of the same order of magnitude.

Computing the ratio of the energy in the N_2 second positive to that in the N_2^+ first negative system for the lines which Meyerott derived, using the absolute intensities in Table III, we get figures of .07 and .02. These do not disagree too badly with Meyerott's number. In preliminary exposures the

wavelength region of 5000 to 6000 Å was examined and no lines were found there. Several of the N_2 first positive lines occur in that interval but the most intense lines have wavelengths greater than 6000 Å. Therefore no definite conclusions can be reached from this data on the validity of Meyerott's estimate of the fluorescence efficiency of this system.

D. Uncertainties

Uncertainties in the absolute intensity arise from two origins. One is the uncertainty that enters the computation of the relative intensities from the density of the film. The estimated uncertainty here is 15 per cent and is derived by observing the variation of density as measured by the densitometer over several exposures. The other uncertainty enters when calibrating the film with the carbon arc. The curve of absolute intensity vs. wavelength for the carbon arc calculated from the Planck formula cannot be matched exactly to the curve of relative intensity vs. wavelength taken from the exposure of the carbon arc. This introduces an uncertainty of about 25 per cent. The total probable error in the values of the absolute intensity is approximately 34 per cent.

E. Calculation of Cross Sections and Yield

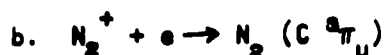
Comparison of excitation-transition cross sections computed from absolute intensities with results of an experiment expressly designed to measure cross sections will give an idea of the degree of confidence with which the results of these experiments can be generalized. Finally, a figure for the yield of radiation energy of the electron collision process will be computed.

Let us consider the reactions by which the excited states of the nitrogen molecule which give rise to the observed spectra are reached.

The second positive (2PG) system of N_2 arises from $C^3\pi_u - B^3\pi_g$ transitions. The $C^3\pi_u$ state can be excited from the ground state of N_2 by either inelastic electron scattering

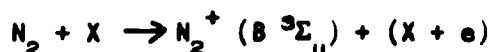


or by the capture of an electron by an N_2^+ ion



The contribution of b. is eliminated in the laboratory by decreasing the air pressure to about 10^{-3} mm or lower. This increases the collisional mean free path of the electrons to more than the dimensions of the region from which light is transmitted to the spectrometer. The capture process requires two collisions, ionization and capture. If we increase the mean free path to more than the dimensions of the emission region then the probability of two collisions occurring in this region becomes very small. Fan¹⁶ has shown experimentally that for pressures less than 10^{-3} mm electron exchange is effectively the only process of excitation to the $C^3\pi_u$ level of N_2 . In our experiment the pressure varied between 10^{-3} to 10^{-2} mm so a small contribution from the capture process would be expected.

The first negative system of N_2^+ arises from the transition $B^3\Sigma_u^+ \rightarrow X^2\Sigma_g^+$ and is excited by the reaction



where X can be an electron. Fan¹⁶ concludes that the contribution of direct excitation from the ground state of N_2^+ must be relatively unimportant. This is reasonable for the pressures used since it would require two collisions.

From the preceding we can see that each photon emitted from the region of the electron beam is the result of one collision between an electron and a molecule. Another indication that this is true is that the current in the beam, including the products of ionization, was roughly proportional to the pressure.

For the scattering process we have the relation

$$\delta I = QNI\delta x \quad 1.$$

where I is the intensity of the primary beam, N is the particle density (nitrogen molecules in our case), Q is the cross section for the process under consideration, and δI is the loss of intensity of the primary beam as it travels a distance δx through the gas. Cross sections for excitations of the N_2 molecule cannot be calculated directly from data on emitted intensity. What can be calculated from experimental data is the cross section for excitation multiplied by a transition probability. For instance, the second positive band system of N_2 involves $C^3\Pi_u - B^3\Pi_g$ transitions. The cross section obtained from the formula would then be the cross section for excitation to the $C^3\Pi_u$ state from the ground state of the N_2 molecule multiplied by the relative probability of the $C^3\Pi_u - B^3\Pi_g$ transition. According to Bates¹⁷ what is obtained experimentally is the excitation-transition cross section given by

$$Q_{jk} = \frac{A_{jk} Q_j}{\sum_k A_{jk}} \quad 2.$$

where $\frac{A_{jk}}{\sum_k A_{jk}}$ is the relative transition probability for transition from the j

to the k state and Q_j is the cross section for excitation to the j state. If the A_{jk} 's can be calculated the excitation cross sections can be computed from spectral intensity measurements.

Q_{jk} for the 4278 Å and 3914 Å bands of the N_2^+ first negative system will be calculated and compared with values obtained from a graph in a paper by Seaton.¹⁸

Experimental conditions must be considered before cross sections can be calculated. The measured beam current consists mainly of primary electrons.

secondary electrons from ionized molecules, and positive ions. We will regard as small other contributions such as secondary electrons due to bombardment of the anode by primary electrons. Langmuir and Jones¹⁹ report that electrons have an ionizing power of about 1 ion per primary electron at an energy of 50 ev increasing to about 1.6 ions per primary electron at 100 ev. We shall consider that the current of primary electrons is about 1/3 the total measured beam current for 50 ev electrons and 1/4 for 100 ev electrons. Table IV shows the results of calculations using the formula

$$Q_{jk} = \frac{\delta I_{jk}}{I} \cdot \frac{1}{N \delta X} \quad 3.$$

where δI_{jk} is the number of photons reaching the film computed from the intensity as measured on the film. δX is about 2 cm

TABLE IV

Excitation-Transition Cross Sections for the 0,1 and 0,0 Bands of the First Negative System of N_2^+

λ	Band (v', v'')	Cross Section $\times 10^{-18} \text{ cm}^2$			
		50 ev		100 ev	
		Ref. 18	Computed	Ref. 18	Computed
4278 A	(0,1)	2	.52	2.2	.15
3914 A	(0,0)	5	3.4	6.0	1.0

Since the cross sections computed from our data agree fairly well in magnitudes with Stewart's¹⁸ values it is concluded that the excitation obtained should be close to those which would be obtained under ideal conditions i.e., monoenergetic primary electrons and a field free excitation region.

It is appropriate to insert here a few words on why conditions were not favorable for observing the integrated intensity of the bands. The spectrometer used had a high dispersion of 8.46 Å/mm and could resolve the structure of each of the vibrational bands. This meant that there was recorded on the film the intensity of each separate line, not the integrated intensity of the whole band as in experiments such as Stewart's. Therefore a higher intensity of light was required in order to make an exposure in a reasonable length of time. In order to get this increased light output, the experimental setup could not be as subtle as it might have been. However, as a result, the relative intensities of a number of the lines in the bands were obtained.

Several assumptions have been implied in the preceding calculations that were not completely justified. The large hole in the anode meant that the region of excitation was not field-free and that the beam of electrons was not monoenergetic. It is difficult to estimate the magnitude of these effects. Of course inhomogeneity of the beam energy was also caused by the Boltzmann distribution of the thermal electrons from the filaments. However, for a tungsten filament kT is less than 1 eV so this effect is probably negligible compared to the effect of the anode hole. Optical absorption was assumed negligible which should be the case at the pressures used. Recombination was ignored since it need not be taken into account at pressures below 10^{-3} mm^{Hg}.

One result which is possible is calculation of a figure giving a measure of the yield of the electron excitation process in radiation in the spectral region examined. We define the yield as the quotient of the rate at which energy leaves the system as radiation divided by the rate at which energy enters the system as kinetic energy of the primary electrons. After the primary electrons have lost most of their energy they will no longer be able to excite the spectral lines which were detected. This lower limit is about 2.5 eV.

The energy available for excitation is therefore about 47.5 ev for the 50 ev primaries and about 97.5 ev for the 100 ev primaries. Taking the sum of the absolute intensities of all the lines that were measureable as the rate at which energy leaves the system as radiation, value of Y of 4.0×10^{-4} and 7.4×10^{-4} were calculated for the 50 ev and 100 ev electron spectra respectively.

We should like to account for the dissipation of all of the energy of the primary electrons. Compton and Voorhis²⁰ give values for the number of ionizing collisions made per cm of path at 0.01 mm pressure at 25°C. They do not give values for oxygen but it is not expected that these will differ much from the values given for N_2 . Therefore we shall take values for N_2 as representative for air. At an energy of 100 ev Compton and Voorhis find that electrons make 0.1 ionizing collisions per cm of path. Since the value from which light goes to the spectrograph has dimensions of the order of 1 cm only $1/10$ of the electron beam will have ionizing collisions in that volume. If we consider the whole bell jar as a volume in which ionizing collisions take place we have to increase the dimension to 75 cm. This would give us a value of 7.5 ionizing collisions per electron before it reaches the wall. This shows that it is very likely that all electrons will undergo ionizing collisions before they reach the wall. It is reasonable that the number of light producing collisions will be proportional to the number of ionizing collisions. In other words, if the number of ionizations is doubled by doubling the path length one would expect the number of photons coming from a certain deexcitation also to be doubled. One is thus justified in increasing the light production efficiency for the whole bell jar by a factor of 75. This brings the total proportion of energy appearing in the spectra to about 5.5×10^{-2} .

Now that we have calculated how much energy leaves the system as light we would like to know what proportion of the electron energy is dissipated before

It strikes the wall. Experiment⁶ shows that an electron loses on the average about 35 ev per ionizing collision. This is the total energy lost per ionizing collision and includes not only the primary ionization energy, which is about 16 ev for N_2 , but also the energy loss due to excitation collisions and the ionizations by secondary electrons. The energy lost per primary ionizing collision in N_2 and O_2 is about 35 ev. From these figures we can see that the electrons should dissipate most of their energy in excitation and ionization collisions before they reach the walls. The probability of recombination of the ions in the gas is very small at the pressures used. Most of the ions will migrate to the walls where they will stay until an electron arrives. The wall serves as a third body for the recombination. Therefore most of the energy will be carried to the walls by ions. Some energy will be emitted in wave length regions outside that examined in this work. It is difficult to make quantitative calculations because little data has been published on the cross sections of the various processes.

One would expect that a portion of the energy of excitation carried to the walls by the ions would eventually be released as spectra in an infinitely large chamber such as the upper atmosphere. The mechanism for this would be recombination with electrons resulting in excited states of the nitrogen molecule.

F. Comparison of Experimental Results with an Observation of an Aurora

Qualitative comparison of the results of this experiment with observations by Barbier²¹ of an aurora show that the principal features closely resemble each other.

Barbier has observed the spectrum of a low altitude aurora in Haute Province, France^{*}. He obtained relative intensities for a number of lines

* His is the most complete analysis of the intensities of the lines of an aurora that could be found by this writer and showed that the first negative and second positive systems of the nitrogen molecule were the strongest lines in the spectrum.

in the first negative system. The lines he observed which fall in our spectral range are 3914, 4278, 3582, 3884, 4236, 3564, 4199 Å. The relative intensities for these lines are 32, 7.9, 8.9, 10, 5.6, 8.9, 0 respectively. The intensities obtained from Table III are normalized to 32 for the 3914 Å line are 32, 4.4, .73, 1.3, .42, 0, small, for 50 ev electrons and 32, 4.3, .68, 1.1, .74, .26, small, for the 100 ev electrons. The best agreement between these sets of data is that the first negative system is responsible for the lines in the spectrum and that within that system the 3914 Å line is much more intense than the others. There is then at least some qualitative agreement between spectra of some aurora and spectra produced in the laboratory by electrons with energies on the order of 100 ev.

Chapter V

Rocket Electron Gun

A. Purpose

It is desired to test the values of the efficiency of the photon production process obtained in the laboratory by sending an electron gun aloft in a rocket. An altitude of 80 to 100 Km will duplicate the pressures used in the laboratory experiments. At altitudes greater than these just as much light should be produced but it will originate in a larger volume so that the source will be more diffuse. It is planned to send the rocket to an altitude of 90 to 100 Km. An Oriole rocket will be used. It will be launched by NASA personnel at Wallops Island, Virginia in late 1961.

B. Payload

The payload of the Oriole rocket will consist of an electron gun, batteries, and a device to separate the payload from the rocket.

The electron guns, consisting of the cathode and grid of a 2E56 tube, were provided by Westinghouse Electric Corp. These should be capable of providing a beam current of approximately one ampere with a filament voltage of 12 volts and an accelerating potential of 150 volts.

The batteries are a silver-zinc type that is the most compact and lightweight per unit output available. Two sets of batteries will be used, one providing power for the filament, the other for the anode. At the rate at which power is to be used, both sets will last about four minutes. No activation procedure, as such, will be followed for the cathode. Filament and anode power will be turned on after the rocket has reached an altitude of at least 50 Km. Emission from the cathode is expected to reach one ampere about one minute after the power is turned on.

The instrument package will be installed in a metal cylinder which will be ejected from the rocket. This was determined to be the simplest way to open the electron gun to the atmosphere.

According to calculations a source of energy of 1.7 watts at a distance of 60 Km should appear as bright as a fifth magnitude star if the light producing process is 100 per cent efficient. Our source of power will make available approximately 150 watts for conversion into light. If the conversion process has an efficiency of greater than one per cent the light should be visible from the ground.

Summary

Listed in Table III are the wavelengths and intensities of spectral lines excited by collisions with air molecules of electrons with energies of 50 ev and 100 ev. In the wavelength interval 3000 Å to 5000 Å the predominant lines in the spectrum are from the first negative band system of N_2^+ and the second positive system of N_2 . Comparison with an observation of an aurora by Barbier shows qualitative agreement between the spectra.

Values of 4×10^{-4} and 7.4×10^{-4} are calculated for the yield of the excitation-emission process, defined as the ratio of the energy emitted as optical radiation to the energy incident as kinetic energy of the primary electrons.

An experiment is described which will yield a measure of the efficiency of the collision-excitation process as a light producing mechanism in the upper atmosphere. An electron gun will be carried by a rocket to an altitude of 90 to 100 Km where electrons with energies of 150 ev will lead to excitation of and emission from the air molecules.

Appendix I

Spectrograph Lineup Procedure

The instrument used to obtain the spectra was a Jarrell-Ash two meter normal incidence vacuum scanning spectrometer. It comes with two gratings:

- a. 600 grooves/mm
wavelength range to about 5400 Å
dispersion is about 8.35 Å/m in 1 order
- b. 1200 grooves/mm
wavelength range to about 2730 Å
dispersion is about 4.18 Å/m in 1 order

The grating area of both is $3\frac{1}{2}'' \times 1\frac{5}{8}''$ and, with either, the spectrometer is capable of resolution of about 0.08 Å in 1 order.

The focusing procedure consists mainly of six parts:

- A. adjusting the grating so that light from the entrance slit falls on the exit slit
- B. aligning the rulings on the grating with the entrance slit
- C. focusing the image of the entrance slit on the exit slot
- D. making adjustments so that the grating entrance slit and the exit slot are all on the Rowland Circle
- E. calibration of wavelength drive
- F. final alignment and focusing

- A.
 1. Turn the wavelength drive until the central image is near the center of the exit slot laterally.
 2. Rotate the grating about its y-y axis by loosening one and tightening the other of the two 8-32 screws vertically opposite each other on the back of the grating mount until the image of the entrance slit is vertically in the middle of the exit slot.
- B.
 1. Illuminate the entrance slit with a mercury lamp and observe one of the lines with an eyepiece. If the grating grooves are parallel to the entrance slit the line will appear as a rectangle. If they are not, it will appear as a parallelogram sloping upward to the right or left. Rotate the grating about the x-x axis until the appearance of the line is correct. This is only an approximate adjustment and must be repeated using film following the other steps.
- C.
 1. Illuminate the entrance slit with a mercury lamp.
 2. Put the slit plate in place so that the largest slit (100μ) is in front of the exit slot.
 3. Determine the position of best focus by moving the grating mount assembly along the optical axis by means of the micrometer screw directly in front of it. Use the Foucault test. The spectrometer is in focus when the illumination of the grating by a spectral line as seen through the exit slit disappears uniformly across the grating.
- D.
 1. Proceeding as in part C, determine whether the spectrometer is in focus in all parts of its spectrum. If it is not, then the grating must be rotated about the z-z axis slightly, and refocused.
 2. If, after rotating the grating, one finds that the position of best focus is beyond the adjustment range of the micrometer screw the camera mount assembly must be rotated slightly about its pivot bar. This requires that one repeat the focusing adjustment and Step 1 in part D.

- E.
1. Illuminate the slit with a mercury lamp.
 2. Operate the wavelength drive reading consistently to higher or lower wavelengths in order to minimize backlash effects. Record the counter wavelength reading at lines whose wavelengths are known and obtain the algebraic difference between consecutive readings.
 3. Make a graph of the algebraic difference against true wavelength. See illustrations on pp. 26 and 27 in Jarrell Ash manual. Repeat step 2 after making small corrections in length of contact arm until line in graph straightens out.
 4. Repeat step 2, making small changes in the sine bar angle until the line in the graph approximates a horizontal straight line.
 5. When a horizontal straight line is achieved, it may be offset from the x-axis. To zero the counter, loosen the wavelength counter, disengage the gears, and set the counter to zero.
 6. The operation should be checked several times.

Of the above operations, E will probably be required the least frequently. For precise work, operations C and D will be required fairly often because of a fault of the machine. The camera mount assembly is not attached to its pivot bar by a secure enough mounting and tends to slip on it when force is applied to the assembly, as in installing the camera. It would be advisable to modify this mounting before attempting precision work with the spectrometer.

F. The final step is to check steps A through E on film.

1. If the line is not long enough vertically and well defined on its ends, the grating must be rotated about the y-y axis.
2. If the image is not evenly lighted it means the grating grooves are not parallel to the entrance slit, or the grating must be rotated about the y-y axis.

3. For final adjustments of focus, take a number of exposures of the same part of the spectrum with different settings of the micrometer screw (at the grating mount assembly) at intervals of 10 divisions. If the lines are examined on a comparator it will also be obvious whether the grating grooves are parallel to the entrance slit.
4. If, in step 3, it is not possible to focus all the lines at the same setting of the micrometer knob, it will be necessary to rotate the grating about the z-z axis until they are all in equally good focus.
5. Repeat Part E.

In step 3 of Part F, the inaccuracy of the wavelength drive will become obvious since the spectrum shifts every time the micrometer knob is adjusted. Another problem stemming from the same source is that a particular position of focus is not repeatable by returning to the same setting of the micrometer knob. Both of these problems are due to the fact that in order to adjust the micrometer knob, a bolt clamping the contact bar with the grating mounting assembly must be loosened to allow adjustment and then tightened again. This loosening and tightening allows the grating mounting assembly and contact bar to shift relative to each other in two directions. One causes the shift of the spectrum, and the other the change in focus position.

Appendix II

The Moon as a Standard of Light Intensity

When one is measuring low levels of light and needs an intensity standard he should remember the heavenly bodies. Their magnitudes are well known and the flux received from them can readily be calculated. As an example, the sensitivity of a 1P21 photomultiplier tube will be measured using light from the full moon.

The full moon has an average apparent visual magnitude of about -12.55. Using the formula

$$M = m + 5 - 5 \log D$$

where M = absolute magnitude, m = apparent magnitude, and D = distance in parsecs (1 parsec = 3.083×10^{13} km), we find that the absolute visual magnitude of the full moon at its average distance of 384,403 km is +31.91. The brightness of the full moon is about 0.26 candles/cm² at its average distance. One must remember, however, that this figure varies about 30% with the changes in the distance between the earth and the moon. To use the brightness multiply it by $(\frac{p_0}{p})^2$ where p_0 is the average distance which is given above and p is the distance at the time of the measurement. Other factors enter to contribute to the experimental uncertainty of the calculated value. The major one is variations in atmospheric conditions which causes variations in the amount of light reaching the observer through changes in the absorption of the atmosphere.

The spectrum of the moon is identical to that of the sun. If one is interested in a particular segment of the spectrum its shape can be calculated from Planck's law using the fact that the sun can be considered a black body radiator with an effective temperature of 6000°K.

If white light is to be considered then the energy flux at the earth is readily calculated. If I_m is the luminous flux received from a star of apparent

magnitude m and in that of the star of magnitude n then, in general,

$$\frac{I_n}{I_m} = (100)^{\frac{m-n}{5}} = (2.512)^{m-n}.$$

The solar constant of 0.07 watts/cm^2 is a well known and convenient number from which to calculate the luminous flux at the earth from any heavenly body. Since the apparent visual magnitude of the sun is -26.72 and that of the moon is -12.55 we have

$$\frac{I_{\text{moon}}}{I_{\text{sun}}} = (100)^{14.17/5} = (100)^{2.83} = 4.66 \times 10^{-5}$$

Therefore,

$$I_{\text{moon}} = .07 \times 4.66 \times 10^{-5} = 3.26 \times 10^{-6} \frac{\text{watts}}{\text{cm}^2} = 3.26 \frac{\mu \text{ watts}}{\text{cm}^2}$$

A measurement was taken of the light falling on a photomultiplier tube from the full moon on a clear night. The photomultiplier, an RCA 1P21, was used with a General Radio Electrometer. The photomultiplier was placed in an aluminum box with a hole in front of the cathode. An eleven inch tube of black paper was placed before the hole to stop out ground lights. The sky in the region of the moon was scanned for a maximum reading on the meter. With an applied voltage of 600 V on the tube and an input resistance in the electrometer of 1 megohm an average reading of $4.9 \pm .3$ volts was recorded on the meter. Since the output resistance of the photomultiplier tube circuit was 0.82 megohm this corresponded to a current of $11 \mu \text{ amp}$. The area of the cathode was 1.89 cm^2 so that the rate at which energy reached it was $1.89 \times 3.26 = 6.2 \mu \text{ watts}$. The sensitivity of the 1P21 photomultiplier tube used to white light was then $11/6.2 = 1.8 \mu \text{ amp}/\mu \text{ watts}$.

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